THE CHEMICAL COMPOSITION OF THE RARE J-TYPE CARBON STARS

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ABSTRACT.
Abundances of lithium, heavy elements and carbon isotope ratios have been measured in 12 J-type galactic carbon stars. The abundance analysis shows that in these stars the abundances of s-process elements with respect to the metallicity are nearly normal. Tc is not present in most of them. The Rb abundances, obtained from the resonance 7800 Å Rb I line, are surprisingly low, probably due to strong non-LTE effects. Lithium and ^{13}C are found to be enhanced in all the stars. These results are used to discuss the origin of J-stars.

1. Introduction

Among the C-stars there exists a significant group of stars ($\sim 15\%$) named J-type stars Bouigue (1954) showing strong ^{13}C-bearing molecule absorptions, which usually implies low ^{12}C/^{13}C ratios (< 15) (e.g. Ohnaka & Tsuji 1999). The location of J-stars in the AGB phase is far from clear. In fact, some authors have located these stars in a different evolutive sequence from that of the ordinary carbon stars (e.g. Chen & Kwok 1993), or even outside the AGB phase. Theoretically, it is not easy to obtain an AGB star with the chemical peculiarities presented by J-stars. Low ^{12}C/^{13}C ratios can be obtained in current AGB star models of M$\geq$ 4 M$_\odot$ by the so-called hot bottom burning (HBB). However, this mechanism at the same time destroys ^{12}C and, in consequence, the C/O ratio in the envelope is reduced and the star again becomes O-rich. Thus, a fine-tuning of the parameters of the AGB models (mass, mixing-length, mass-loss rate, metallicity, etc.), that determine the chemistry of the envelope, is required to obtain a J-star.

The presence of strong λ6708 Å Li I lines is frequent in J-stars. About 70% of the galactic J-stars observed are Li-rich (Boffin et al. 1993). Interestingly, HBB can simultaneously produce Li-rich and ^{13}C-rich AGB stars in models with initial mass M$\geq$ 4 M$_\odot$. However, observations indicate that the majority of C-stars in the galaxy are low-mass objects, M$\leq 2-3$ M$_\odot$ (e.g. Claussen et al. 1987). For this mass range no HBB has been found in any AGB model. An important consequence of the third dredge-up (TDU) in the AGB phase is the enrichment of the envelope with s-process elements. These elements are believed to be synthesized during the period between thermal pulses via the ^{13}C(α,n)^{16}O reaction as the neutron source. Thus, if J-type stars owe their ^{12}C enhancement to the operation of the TDU, *they should also show some s-process element enrichment.*

In this work we perform a detailed abundance analysis of twelve galactic J-type carbon stars using very high resolution and signal-to-noise ratio echelle spectra. Our results, together with CNO and Li abundances determined in other studies, are contrasted with theoretical stellar models to find an evolutionary status for J-type stars.

2. Observations

Details on observations, intrumentation used and data reduction can be found in Abia et al. (1999). Our stars fullfil the criteria for the ^{13}C abundance by Keenan (1993) to be classified as J-stars. However, WZ Cas shows weaker CN and C_2 band absorptions than the other J-stars in the sample. It also shows very strong Na D lines and its spectrum does not look as crowded as the rest of the J-stars. Indeed, this happens when the C/O ratio in the atmosphere is very close to unity, a characteristic which defines a SC-type carbon star. Since our C/O estimate in this star is ~ 1.01, we believe that WZ Cas has to be considered a SC-star rather than a typical J-star. Furthermore, it is the most luminous star in our sample ($M_{\rm bol} \sim -6.44$), which could indicate that WZ Cas belongs to a different population (massive) of C-stars or that it is in a different evolutionary status (more evolved) than the rest of the J-stars in our sample. Less obviously, the same peculiarities are observed in the spectrum of WX Cyg although for this star, we do not have a clear opinion about its spectral type. To estimate absolute bolometric magnitudes $M_{\rm bol}$ of our stars we have used the empirical relationships between $M_{\rm bol}$ and M_K-M_V for C-stars obtained by Alksnis et al. (1998). To obtain M_K and M_V, the K and V average values (the stars studied are variable!) quoted in the SIMBAD database were used. K and V magnitudes were corrected for interstellar extinction according to the galactic extinction model by Arenou et al. (1992). Distances were derived from parallax measurements by HIPPARCOS. Some parallaxes have considerable erros, thus the absolute magnitudes derived have to be considered as average values and only indicative.

3. Analysis

For the majority of the stars studied here the effective temperature is derived by Ohnaka & Tsuji (1999) using the infrared flux method. For some stars we used the $(J - L')_o$ vs. $T_{\rm eff}$ calibration also described by Ohnaka & Tsuji (1996). The set of models used in this analysis was computed by the Uppsala group (see Eriksson et al. 1984, for details). The input elemental abundances adopted for the J-star models were the solar values, with the exception of C, N and O which were assumed to be altered relative to the Sun. For each star a model atmosphere was interpolated in $T_{\rm eff}$ and C/O ratio in this grid. A typical microturbulence velocity for AGB stars $\xi = 3$ kms^{-1} was adopted or taken from the literature when available Lambert et al. (1986).

Basically, we have used three atlases for atomic line identification. These are those by Utsumi (1970) in the region between $\lambda 4400 - 4500$ and $\lambda 4750 - 4900$ Å, and by Wallerstein (1989) and Barnbaum et al. (1994) in the region, $\lambda \sim 5000 - 8000$ Å. We followed the same criteria as in Abia & Wallerstein (1998; hereafter Paper I) to consider an identification as useful for abundance analysis. We refer the reader to this paper for details. Unfortunately, very few lines were found to be useful for analysis depsite

several hundred atomic lines were searched in each star. For some species only *one* line was found. Equivalent widths of the lines were measured with the SPLOT program of the IRAF package. We estimate the error in the equivalent width from the theoretical expression given in Paper I: $\Delta W(\lambda) = 10$ to 35 mÅ, according to the line intensity and to the S/N of the spectrum, with the main uncertainty being introduced by the continuum placing. When possible, gf values were derived from identification and equivalent width measurements in the Solar Atlas by Moore et al. (1966), using solar abundances from Anders & Grevese (1989). Otherwise, we used the gf-values given in the VALD database (Piskunov et al. 1995).

4. Abundance results

Table 1 shows our abundance results. The Li abundances were derived by spectrum synthesis and corrected by N-LTE effects according to Abia et al. (1999). From Table 1 it is clear that all the stars have unusual Li abundances ($\log \epsilon(\mathrm{Li}) \geq 1$). WX Cyg and WZ Cas are certainly super Li-rich stars, although these stars may not be J-type stars (see above). Figure 1 shows the correlation of Li abundances versus $^{12}C/^{13}C$ ratios found in J- (this work) and N-type carbon stars (Abia & Isern 1997).

This study is the first detailed search for the presence of Tc in J-type stars. We have used the intercombination Tc line at λ5924.47 Å. We followed the same procedure in the analysis as in Paper I. As there, the λ5924 Tc blend is not well reproduced by synthetic spectra. Thus, we prefer to be cautious and record the Tc abundance as equal-to-or-less-than. In most of the stars, the best fit to the Tc blend is compatible with no-Tc. For these stars we quote a *no* entry in Table 1, meaning that Tc, very probably, is not present. Leaving apart the upper limits set for WZ Cas and WX Cyg, possible SC-type stars, we can conclude that most of J-stars do not show Tc.

We have used the resonance line at λ7800.23 Å to derive Rb abundances. We refer again to Paper I for a discussion of the identification of the atomic and molecular lines contributing to the Rb blend. Only in three stars (WX Cyg, WZ Cas and V353 Cas) does the Rb line appear clearly as a prominent absorption in the background of CN lines. In the remaining stars the Rb line is not distinguished from the background of lines. Table 1 shows the Rb abundance derived in our stars relative to their mean metallicity [M/H][1]. From Table 1 it is apparent that the [Rb/M] ratios derived are remarkably low. For some stars the best fit is compatible with *no* Rb. Nevertheless, we believe that our Rb abundances could be, and in some cases are, lower limits probably due to strong N-LTE effects in the formation of the Rb resonance line in cool C-rich atmospheres (see Abia & Isern 1999).

The abundances of metals were derived from the usual method of equivalent width measurements and curves of growth calculated in LTE. Ca, V, Fe and Ti abundances were used as a measure of the metallicity of the stars. The [M/H] value shown in Table 1 is the mean metallicity obtained from these elements. Table 1 also shows the heavy-element abundance ratios respect to the metallicity derived in the sample stars. We derive the mean heavy-element enhancement $[< h >/\mathrm{M}]$ in each star. To derive this we did not consider upper limits or the uncertain Rb abundances. The formal error in the

[1] We adopt here the usual notation $[\mathrm{X}] \equiv \log(\mathrm{X})_\star - \log(\mathrm{X})_\odot$ for any abundance quantity X.

Table 1. Abundances Derived in Program Stars

Specie	WX Cyg	WZ Cas	VX And	UV Cam	Y CVn	FO Ser	BM Gem	RY Dra	RX Peg	V614 Mon	V353 Cas
Li	4.4	4.8	2.6	3.0	0.7	1.2	1.5	1.3	1.5	1.3	2.7
Tc	< 0.7	< 1.0	no	no	no	no	no	no	no	no	no
[M/H]	0.3	0.0	0.05	0.2	0.0	0.1	0.2	-0.05	0.4	-0.1	0.3
[Rb/M]	-0.35	-0.55	-1.15	-1.10	-1.60	no	-1.60	no	-1.25	no	-0.90
[Sr/M]	<0.7	0.3	<0.5	<0.7	...	<0.5	<0.5	<0.9	<0.3	<0.5	...
[Y/M]	-0.45	-0.1	...	-0.05	<0.6	0.25	<0.7	0.3	0.1	0.16	0.20
[Zr/M]	-0.3	0.2	...	-0.15	0.2	0.0	0.15	...	-0.3	...	...
[Nb/M]	<1.1	0.3	0.15	0.17	...	...	...	<0.5	...	0.10	...
[Ba/M]	0.0	0.4	0.25	-0.07	0.3	0.1	-0.2	0.1	-0.4	0.27	
[La/M]	-0.25	-0.1	...	0.3	...	...	...	...	...	...	...
[Ce/M]	0.3	0.15	...	0.25	...	...	...	...	0.05	...	...
[Pr/M]	0.2	0.15	...	0.0	...	...	...	...	...	...	...
[Nd/M]	0.05	...	...	0.3	0.4	0.5	0.1	0.35	0.0	<0.6	0.15
[Sm/M]	...	...	...	...	...	<0.5	...	...	0.1	...	...
[Gd/M]	<0.6	...	...	...	...	...	...	...	...	...	...

Fig. 1.

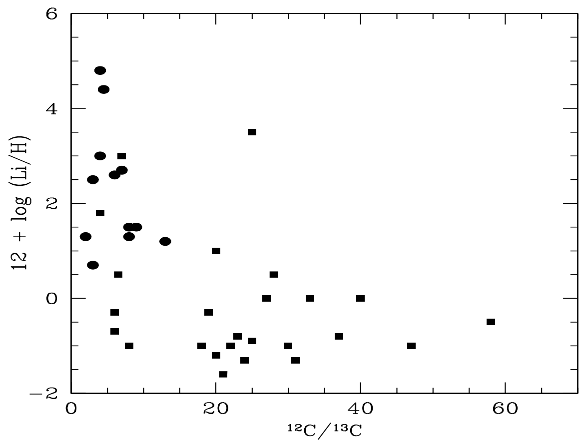

Fig. 2. Li abundances vs. $^{12}C/^{13}C$ ratios in J-stars (circles) in this work and normal (N) carbon stars (squares) from Abia & Isern (1997)

heavy-element abundances shown in Table 1, range from $\pm 0.3 - 0.6$ dex. Taking this error bar into account our results show that J-type C-stars are of near solar metallicity $\overline{[M/H]} = 0.12 \pm 0.16$, the mean heavy element enhancement among the J-stars in the sample being $[< h >/M] = 0.13 \pm 0.12$, which is compatible with *non-enrichment*.

5. Evolutionary Considerations

Figure 2 shows the position of our J-stars in an observational H-R diagram, including some galactic R-type and N-type carbon stars with absolute magnitudes also derived from the HIPPARCOS parallaxes. From this figure, one might consider J-stars as transition objects between R-stars and N-stars. This is reinforced considering the fact that most J-stars are irregular or semi-irregular variables (very few Miras are found among them) with not very large pulsation periods, which is a characteristic of the less evolved carbon stars.

Current AGB models (see Lattanzio, this proceeding) can obtain C-rich envelopes and low carbon isotope ratios in stars with initial mass $M \geq 4\ M_{\odot}$ through the successive He-shell flashes and TDU episodes coupled with the operation of HBB. These stars can also be, for a long period of time, Li-rich stars. However, the operation of HBB leads to the transformation of ^{12}C into ^{14}N; thus nitrogen is expected to be enhanced in these stars. The nitrogen abundances derived in some J-stars (Lambert et al. 1986) show a normal N/O ratio, much lower than that expected on the basis of the CNO cycle operation in HBB. Theoretical models can only obtain a C-rich, Li-rich, $^{12}C/^{13}C$ low and $N/O < 1$ AGB star in a very narrow range of stellar masses ($M \sim 5\ M_{\odot}$), with a specific metallicity ($Z \sim Z_{\odot}/3$) and for a very short period of time ($\leq 10^4$ yr). In this context, the number of J-stars expected would be very low, which is in contrast with the significant number observed. On the other hand, these objects would be fairly luminous

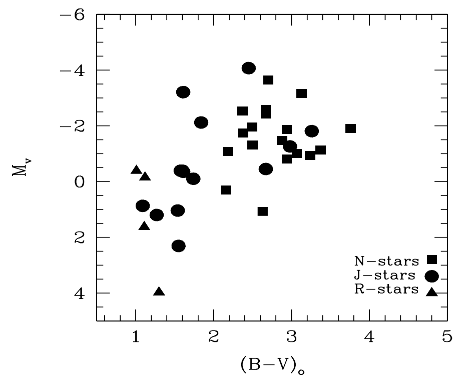

Fig. 3. Observational H-R diagram of galactic carbon stars of different types.

($M_{bol} < -6$), and should present some s-process element enhancement. None of this is observed. Wasserburg et al. (1995) have porposed the existence of a non-standard mixing mechanism which might transport material from the bottom of the convective envelope into deeper and hotter regions where a *cool processing* might occur. This hypothetical mixing mechanism has been shown to reproduce the CNO isotope anomalies found in some low-mass red giants (Boothroyd & Sackmann 1999). Under certain conditions, it can also create ^{7}Li via the Cameron & Fowler (1971) mechanism, thus accounting for the recent discovery of surprisingly high lithium abundances in some low-mass red giants. Boothroyd & Sackmann suggest that this extra-mixing and cool bottom processing could also occur in low-mass ($\leq 2-3$ $M_\odot$) stars on the early-AGB or just after the onset of the helium shell flashes. This point might be compatible with the suggestion (Figure 2) that J-stars are not very evolved AGB. In that case, little or no s-process element enhancement would be expected, as a significant number of TDU episodes are needed. This might also be compatible with the abundance results presented here.

Next, we examine a scenario outside the AGB phase: the mixing at the He-flash. This mechanism has already been proposed to explain the evolutionary status of the R-stars (Dominy 1985). Note that as far as the chemical composition is concerned, R-stars and J-stars only differ in the presence of Li and slightly lower ^{12}C/^{13}C ratios in the latter. Recently, Deupree & Wallace (1996) have re-examined the He-core flash performing hellium flash calculations of different intensity. The authors estimate the surface abundance anomalies produced by He-flashes with different peak temperatures. They show that the primary material mixed into and above the H-shell in all cases is ^{12}C. For peak temperatures $\sim 9\times10^8$ K, important ^{12}C enhancements can be obtained in solar metallicity stars, in shuch a way that the star might become a carbon star.

Interestingly, Deupree & Wallace claim that their flash computations do not produce s-process elements while Li production would require temperatures not exceeding $\sim 5 \times 10^7$ K in the processing zone. This temperature requirement, however, appear rather difficult to attain (Lattanzio, private communication).

Finally, we consider the mass-transfer scenario in a binary system. It is difficult to explain the absence of s-process element enhancement and the C/O ratios in our stars within this scenario. In principle, the accreted material must be extremely carbon-rich; the donor star should be a normal C-star with probably enhanced s-nuclei in the envelope. It is easy to estimate that a C/O$\geq$ 5 in the material accreted is needed by a *typical* ~ 1 $M_\odot$ red giant when applying this scenario to explain the C/O$>$ 1 ratios observed. This extreme C/O ratio is not observed in any C-star. Furthermore, it is unlikely that Li could survive during the mass-transfer and posterior mixing. In fact, extrinsic (binary, no Tc) S stars do not usually show the Li enhancements found here (Barbuy et al. 1992). Nevertheless, a significant number of J-stars (5% $-$ 10%, LLoyd-Evans 1991) show a very uniform 9.85 μm emission which is believed to be due to the presence of a silicate dust shell. Silicate emission is usually associated with O-rich environments, while J-stars are C-rich objects. It has been suggested (e.g. LLoyd-Evans 1991) that the material expelled from the now carbon star, starting while it still had an oxygen-rich envelope, has accumulated in a disc (or common envelope) around an unseen hypothetical companion. In fact, Barnbaum et al. (1991) found significant radial velocity variations in BM Gem and EU And. This result point out to a binary nature for these two J-type carbon stars. Although the binary hypothesis can probably explain the silicate emission in some J-stars, it is difficult to explain how binarity can induce the chemical properties of J-stars. Uunfortunately there are not other radial velocity variation studies nor a search for ultraviolet excesses (in the hypothesis that the companion is now a white dwarf) to test this scenario for all the observed J-stars.

6. Conclusions

Our most important conclusion is that heavy element abundances in J-type carbon stars are nearly solar with respect to their metallicity. We did not found Tc in most of the stars. Considering all our abundance results, it is difficult to find an evolutionary status for J-stars. Their average luminosity and variability types leads us to consider these objects as less evolved than normal (N) carbon stars. However, standard AGB models are unable to explain all their properties. On the contrary, the chemical peculiarities of J-stars suggests the existence of a non-standard mixing mechanism, similar to that proposed in the red giant branch to explain anomalous CNO isotopic ratios and Li abundances. This extra-mixing mechanism, would act preferably in the early AGB phase of low-mass stars (M$\leq 2 - 3$ $M_\odot$). Mixing at the He-core flash and the binary system hypothesis may well be alternative scenarios, although fine tuning is required to explain all the observed characteristics of J-stars within these models.

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